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Fat Tails and the Social Cost of Carbon[†]

By Martin L. Weitzman*

At high enough greenhouse gas (GHG) concentrations, climate change might conceivably cause catastrophic damages with small but nonnegligible probabilities. Other things being equal, this should lower the discount rate used to evaluate mitigation-investment decisions and raise the social cost of carbon (SCC). If the bad tail of climate damages is sufficiently fat with probability, and if the utility function has relative risk aversion greater than one, then (at least in theory for at least some formulations) this insurance-like catastrophe-reducing aspect of mitigation investments can be very powerful. In the most extreme limit this tail-hedge insurance effect can be infinitely strong and can dominate the economic analysis by making the SCC infinite. This kind of extreme (and empirically unbelievable) limiting result is a version of what I have previously labeled the "dismal theorem."[1]

In this paper I use the simplest possible model to lay bare the basic structure of the argument, then attempt to place the underlying issues in balanced perspective. The "dismal theorem" of an infinite SCC is a theoretical limiting result which relies on particular assumptions that may or may not have actual relevance for climate-change policy depending upon the interaction of a variety of empirical factors, functional forms, and parameter values. I argue that the main value of the "dismal theorem" is to serve as a warning flag that a credible economic analysis of climate change should seriously consider extreme tail values of damages and their associated probabilities because they may have the potential to increase the SCC significantly.

I. A Super-Simple Expository Model

The simplistic model here has two periods. Some base case of abatement strategy is given. All consumption refers to "effective consumption"—*after* climate change damages have been subtracted. The utility of consumption is $U(C)$. Present consumption is C_0. Future consumption is the random variable $\tilde{C}$, whose expected utility is discounted by β. Welfare is $W = U(C_0) + \beta E[U(\tilde{C})]$, where E is the expectation operator. Let $\underline{C}$ represent a catastrophic low value of effective consumption that occurs with probability p, where both $\underline{C}$ and p are considered to be "very small."

Suppose that one extra unit of carbon abatement uniformly shifts upwards future consumption by the multiplicative factor $\theta > 0$. (This is consistent with having a multiplicative damages function.) For utmost simplicity, I now analyze *only* the effect upon the catastrophe outcome, which is the main focus of attention for this paper. The effect is that with probability p the postabatement level of catastrophic consumption is now $(1 + \theta)\underline{C}$, instead of the preabatement level of $\underline{C}$. Abatement here induces first-order stochastic dominance via an upward shift in the probability-p point mass $\underline{C} \to (1 + \theta)\underline{C}$.

The *social cost of carbon* (SCC) is the (negative of the) change in C_0 per small change in abatement that would give the same level of welfare W as before. In words, it is the willingness to pay for a small extra unit of abatement.[2] Assume utility is of the CRRA form $U(C) = C^{1-\eta}/(1 - \eta)$, where the coefficient of relative risk aversion is $\eta > 1$. Normalize $C_0 = 1$. With this specification, the *SCC* here is readily calculated to be

$$(1) \qquad SCC = \beta\theta[p\underline{C}^{1-\eta}].$$

*Economics Department, Harvard University, Littauer Center, Cambridge, MA 02138 (e-mail: mweitzman@harvard.edu).

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[1] See Weitzman (2009, 2011).

[2] A procedure for empirically deriving the SCC is described, e.g., in Greenstone, Kopits, and Wolverton (2013).

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On Not Revisiting Official Discount Rates: Institutional Inertia and the Social Cost of Carbon†

By Cass R. Sunstein*

Within the executive branch, important decisions result from both substantive judgments and institutional constraints. The constraints take the form of three sets of costs: decision costs, opportunity costs, and political costs. In exploring the workings of government, economists and economically oriented law professors have placed far too much emphasis on the role of interest groups and far too little emphasis on a far larger set of institutional constraints, of which interest-group activity is at most one part. Because of those constraints, it can be costly and difficult to change existing policies, especially when such changes typically require a consensus among diverse people, who may have strong views and who have many demands on their time. For public officials, a degree of institutional inertia is often a product of a considered analysis of the full set of costs and benefits. Both decision costs and error costs must be taken into account.

With respect to discount rates in the domain of regulation, the central governing document is Office of Management and Budget (OMB) Circular A-4, issued in 2003 (OMB 2003). Circular A-4 was produced by officials within the executive branch, coming from diverse parts of the federal government; both political appointees and career officials played a role. The Council of Economic Advisers and the Office of Information and Regulatory Affairs (OIRA) were particularly important. An initial version was presented to the public for comments and also subjected to peer review. OMB Circular A-4 calls for discount rates of 7 percent "whenever the main effect of a regulation is to displace or alter the use of capital in the private sector" and 3 percent "when regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services)" (OMB 2003). Emphasizing both ethical considerations and the role of uncertainty with respect to interest rates over time (Weitzman 1998), Circular A-4 also allows "a further sensitivity analysis using a lower but positive discount rate" when a rule "will have important intergenerational benefits or costs" (OMB 2003).

With respect to climate change in particular, the relevant guidance, coming in the form of a Technical Support Document (TSD), was issued by the Interagency Working Group on Social Cost of Carbon in 2010 (Interagency Working Group 2010; Greenstone, Kopits, and Wolverton 2011). The Interagency Working Group, which I helped to convene, included representatives of the Council of Economic Advisers, the Council on Environmental Quality, the Department of Agriculture, the Department of Commerce, the Department of Energy, the Department of Transportation, the Environmental Protection Agency, the National Economic Council, the Office of Energy and Climate Change, the Office of Management and Budget, the Office of Science and Technology Policy, and the Department of the Treasury. The resulting document describes the monetary value of reductions in carbon emissions, in a way that bears on a large number of regulatory judgments. In that sense, the United States has in fact "put a price on carbon."

Importantly, the TSD adopts a global, rather than merely domestic, measure of damages; harms to people in China, Europe, Africa, and India are counted. The TSD notes that climate change involves "a global externality," that it "presents a problem that the United States alone cannot solve," and that "the United States has

* Robert Walmsley University Professor, Harvard Law School, Harvard University, 1563 Massachusetts Avenue, Cambridge, MA 02138 (e-mail: csunstei@law.harvard.edu).
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convective precipitation likely to increase more rapidly than stratiform precipitation[8,9]. However, other changes — such as shifts in large-scale circulation patterns — may have different responses to climate change in different seasons[10], and this can also influence trends in extreme precipitation intensity, as observed here. Simulating the combined effect of all of these processes remains a major challenge in climate modelling. Although some recent modelling studies have emphasized sub-daily precipitation[11], more work is needed to understand the dominant processes that govern changes in extreme precipitation at both short (sub-daily and sub-hourly) and long timescales.

Given the fundamental relationship between catchment size, the duration of an extreme precipitation event and flood magnitude[12], the finding that extreme precipitation is changing at different timescales has potentially surprising implications for flood risk. Our results show that different or even opposing trends in flood risk are possible within a single geographic region, such as neighbouring catchments of different sizes, or even smaller sub-catchments within the same larger basin. This will be of interest to those involved in land-use planning, water infrastructure design (for example dams, levees, bridges and storm-water drainage networks), floodplain management, emergency response, as well as to the insurance industry. ❒

References
1. Boucher, O. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 7 (IPCC, Cambridge Univ. Press, 2013).
2. Westra, S. *et al. Rev. Geophys.* **52,** 522–555 (2014).
3. Field, C. B. *et al.* (eds) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, Cambridge Univ. Press, 2012).
4. Westra, S. & Sisson, S. *J. Hydrol.* **406,** 119–128 (2011).
5. Westra, S. *et al. J. Clim.* **26,** 3904–3918 (2013).
6. Delworth, T. L. & Zeng, F. *Nature Geosci.* **7,** 583–587 (2014).
7. *Summary of Climate Change Impacts Sydney Region* (Department of Environment and Climate Change New South Wales, 2008); http://www.environment.nsw.gov.au/resources/climatechange/08519Sydney.pdf
8. Lenderink, G. & Van Meijgaard, E. *Nature Geosci.* **1,** 511–514 (2008).
9. Berg, P., Moseley, C. & Haerter, J. O. *Nature Geosci.* **6,** 181–185 (2013).
10. Grose, M. *et al. Clim. Dynam.* **39,** 445–459 (2012).
11. Kendon, E. J. *et al. Nature Clim. Change* **4,** 570–576 (2014).
12. Brutsaert, W. *Hydrology — An Introduction* (Cambridge Univ. Press, 2005).

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Additional information
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Feifei Zheng, Seth Westra* and Michael Leonard
School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, South Australia 5005, Australia.
*e-mail: seth.westra@adelaide.edu.au

CORRESPONDENCE:

IAMs and peer review

To the Editor — Integrated assessment models (IAMs) have provided the bulk of the evidence relied on by prominent documents — such as the Stern Report[1] and the contributions of Working Group III to the IPCC Assessment Reports[2,3] — as well as numerous research articles on the economics of climate change mitigation and related issues. I am concerned, however, that many published IAM-based research articles fail to adequately explain the basis for their findings, and do not justify these findings carefully based on sound scientific and logical argumentation, analysis, and data presented in the article itself (or in published appendices). Often the details of how the IAMs were used to derive the basic results are not described, meaning that reviewers cannot credibly assess the reliability of the results.

One major flaw of most, if not all, peer reviews of IAM-based research reports is that the models relied upon have not been reviewed in themselves. And yet such articles cannot be adequately reviewed without carefully critiquing the underlying models. All too often the original models, and subsequent versions, have never been formally peer reviewed publicly. Due to these shortcomings, even the recent 'model intercomparison projects'[4] are, I would argue, of limited value.

Because economics claims to be a science, and because economists have developed many different IAMs, peer reviewers of IAM-based research articles should, in my view, assess: (1) the theory behind each model in light of model's intended purpose; (2) the structure of the model to determine if the theory was properly implemented; (3) the way in which various structural parameters were estimated based on historical data; and (4) the way in which the values of various input parameters were estimated or derived, especially those for the future. The last point is a particular problem because many IAM-based studies involve very long-term, multi-decadal projections. In addition, I believe that peer reviewers must especially assess how the model is being used in relation to the particular research questions being addressed, and what sensitivity analyses have been performed that might illuminate the answers to these questions. If any of these steps are skipped, then confidence in the reported findings is reduced. Of course, if some of these steps have been undertaken for previously published articles using the same IAM, and if the model has not significantly changed since these reviews were completed, then some of the above steps could be deemed to be complete prior to the current review. It would be helpful in this regard if past reviews of the particular IAM were made available in some format. But this is almost never done.

In 2013, the IAM Consortium — which was set up at the request of the IPCC after the Fourth Assessment Report and of which I am a member — set up scientific working groups intending to establish community-wide standards on IAM documentation and the inclusion of key input assumptions in research publications. There has been little or no progress since. It is my contention that this situation should be rectified, so as to usher in a new era for peer reviews in this field. ❒

References
1. Stern, N. *The Economics of Climate Change – The Stern Review* (Cambridge Univ. Press, 2007).
2. IPCC *Climate Change 2007: Mitigation of Climate Change* (eds Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. & Meyer, L.A.) (Cambridge Univ. Press, 2007).
3. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).
4. Rosen, R. A. *Technol. Forecast. Soc. Change* http://dx.doi.org/10.1016/j.techfore.2015.01.019 (2015).

Richard A. Rosen
Tellus Institute, 11 Arlington Street, Boston, Massachusetts 02116-3411, USA. e-mail: rrosen@tellus.org

CORRESPONDENCE:

Long history of IAM comparisons

To the Editor — We agree with the point made in a recent Editorial in this journal[1] that the assumptions behind models of all types, including integrated assessment models (IAMs), should be as transparent as possible. However, it is incorrect to imply that the IAM community is just "now emulating the efforts of climate researchers by instigating their own model inter-comparison projects."

In fact, model comparisons for integrated assessment and climate models followed a remarkably similar trajectory. Early general circulation model (GCM) comparison efforts[2] evolved to the first Atmospheric Model Inter-comparison Project (AMIP), which was initiated in the early 1990s[3]. Atmospheric models developed into coupled atmosphere–ocean models (AOGCMs) and results from the first Coupled Model Inter-Comparison Project (CMIP1) became available about a decade later[4].

Results of first energy model comparison exercise, conducted under the auspices of the Stanford Energy Modeling Forum, were published in 1977[5]. A summary of the first comparison focused on climate change was published in 1993[6]. As energy models were coupled to simple economic and climate models to form IAMs, the first comparison exercise for IAMs (EMF 14; https://emf.stanford.edu/projects) was initiated in 1994, and IAM comparison exercises have been ongoing since this time[7–10] — and were recently assessed in the latest IPCC report[11] — including a publicly accessible database of scenarios (https://secure.iiasa.ac.at/web-apps/ene/AR5DB). ❐

References

1. *Nature Clim. Change* **5,** 81 (2015).
2. *Understanding Climatic Change* Appendix B (National Academy of Sciences, 1975).
3. Gates, W. L. *et al. Bull. Am. Meteorol. Soc.* **80,** 29–55 (1999).
4. Covey, C. *et al. Clim. Dynam.* **16,** 775–787 (2000).
5. EMF Working Group *Energy and the Economy: EMF Report 1* (Stanford Univ., 1977).
6. Gaskins, D. W. Jr & Weyant, J. P. *Am. Econ. Rev.* **83,** 318–323 (1993).
7. Kriegler, E. *et al. Technol. Forecast. Soc. Change* **90,** 24–44 (2015).
8. Calvin, K. L. *et al. Energy Econ.* **34** (suppl. 3), S251–S260 (2012).
9. Edenhofer, O. *et al. Energy J.* **31** (special issue), 11–48 (2010).
10. Luderer, G. *et al. Climatic Change* **114,** 9–37 (2012).
11. Clarke L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).

Steven J. Smith[1]*, Leon E. Clarke[1], James A Edmonds[1], Jiang Kejun[2], Elmar Kriegler[3], Toshihiko Masui[4], Keywan Riahi[5], Priyadarshi R. Shukla[6], Massimo Tavoni[7], Detlef P. van Vuuren[8,9] and John P. Weyant[10]

[1]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland 20740, USA. [2]Energy Research Institute, B1505, Guohong Building, Jia.No.11, Muxidibeili, Xicheng District, Beijing 100038, China. [3]Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany. [4]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan. [5]International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria. [6]Indian Institute of Management, Vastapur, Ahmedabad 380015, India. [7]Fondazione Eni Enrico Mattei (FEEM), Corso Magenta 63, 20123 Milano, Italy. [8]PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, the Netherlands. [9]Faculty of Geosciences, Utrecht University, 3584 CS Utrecht, the Netherlands. [10]Department of Management Science and Engineering, Stanford University, Stanford, California 94305, USA.
*e-mail: ssmith@pnl.gov

CORRESPONDENCE:

Strategies for changing the intellectual climate

To the Editor — Castree *et al.*[1] are correct that a 'single, seamless concept of integrated knowledge' cannot do justice to the diversity of meanings that need to be brought to bear in addressing the challenges of global environmental change. We also agree with them that environmental social sciences and humanities (ESSH) can make important contributions to global environmental change (GEC) science. However, their charge that we ignore the full range of anthropological contributions to understanding of climate change reflects a misreading of our recent Perspective[2] in this journal, as we only attempted to discuss a few exemplary strands of the many contributions from anthropology to a richer understanding of climate change (for a more detailed discussion, see our forthcoming edited volume[3]).

Secondly, Castree *et al.* suggest that we are reinforcing the status quo in GEC science and 'pulling our punches' by using terms common in Earth systems science (such as system and mechanism). Our use of such terms reflected a strategy to use familiar language to raise awareness of anthropological contributions little known to most GEC scientists, along the lines of the 'clumsy solutions' proposed by anthropologist Steven Rayner[4]. Rayner calls for these solutions to 'wicked problems' such as climate change — problems marked by deep underlying conflicts about the nature of the problem itself — because they can allow different actors to work together without sharing ethical or epistemological principles. We agree with Castree *et al.* that other strategies are possible, but not that theirs is the only route to a wider dialogue.

Castree *et al.* focus on three texts to illustrate how GEC scientists evoke the notion of seamless, totalizing knowledge. They single out the use of terms such as 'integration' in discussions of knowledge to

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The social cost of atmospheric release

Drew T. Shindell

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Abstract I present a multi-impact economic valuation framework called the Social Cost of Atmospheric Release (SCAR) that extends the Social Cost of Carbon (SCC) used previously for carbon dioxide (CO_2) to a broader range of pollutants and impacts. Values consistently incorporate health impacts of air quality along with climate damages. The latter include damages associated with aerosol-induced hydrologic cycle changes that lead to net climate benefits when reducing cooling aerosols. Evaluating a 1 % reduction in current global emissions, benefits with a high discount rate are greatest for reductions of co-emitted products of incomplete combustion (PIC), followed by sulfur dioxide (SO_2), nitrogen oxides (NO_x) and then CO_2, ammonia and methane. With a low discount rate, benefits are greatest for PIC, with CO_2 and SO_2 next, followed by NO_x and methane. These results suggest that efforts to mitigate atmosphere-related environmental damages should target a broad set of emissions including CO_2, methane and aerosol/ozone precursors. Illustrative calculations indicate environmental damages are \$330-970 billion yr^{-1} for current US electricity generation (~14–34¢ per kWh for coal, ~4–18¢ for gas) and \$3.80 (-1.80/+2.10) per gallon of gasoline (\$4.80 (-3.10/+3.50) per gallon for diesel). These results suggest that total atmosphere-related environmental damages plus generation costs are much greater for coal-fired power than other types of electricity generation, and that damages associated with gasoline vehicles substantially exceed those for electric vehicles.

1 Introduction

Societal assessment of environmental threats depends upon a variety of factors including physical science-based estimates of the risk of impacts and economic valuation of those impacts. Quantitative estimates of costs and benefits associated with particular policy options can inform responses, but such valuations face a myriad of issues, including the choice of which impacts to 'internalize' within the economic valuation, the value of future versus present risk, and how to compare different types of impacts on a common scale (e.g. (Arrow et al. 2013; European Commission 1995; Johnson and Hope 2012; Muller et al. 2011; National Research Council 2010, hereafter NRC2010; Nordhaus and Boyer 2000)).

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D. T. Shindell (*)
Nicholas School of the Environment, Duke University, PO Box 90328, Durham, NC 27708, USA
e-mail: drew.shindell@duke.edu

Fran Sussman*, Christopher P. Weaver and Anne Grambsch

Challenges in applying the paradigm of welfare economics to climate change

Abstract: This paper discusses the challenges inherent in developing benefit-cost analysis (BCAs) of climate change. Challenges are explored from three perspectives: meeting the foundational premises for conducting BCA within the framework of welfare economics, methodological considerations that affect the application of the tools and techniques of BCA, and practical limitations that arise out of resource constraints and the nature of the question, project, or policy being evaluated. Although economic analysts frequently face – and overcome – conceptual and practical complications in developing BCAs, climate change presents difficulties beyond those posed by more conventional environmental problems. Five characteristics of the climate system and associated impacts on human and natural systems are identified that pose particular challenges to BCA of climate change, including ubiquity of impacts, intangibility, non-marginal changes, long timeframes, and uncertainty. These characteristics interact with traditional economic challenges, such as valuing non-market impact, addressing non-marginal changes, accounting for low-probability but high-impact events, and the eternal issue of appropriately discounting the future. A mapping between the characteristics of climate change and traditional economic challenges highlights the difficulties analysts are likely to encounter in conducting BCA. Despite these challenges, the paper argues that the fundamental ability of economic analysis to evaluate alternatives and tradeoffs is vital to decision making. Climate-related decisions span a wide range in terms of their scope, complexity, and depth, and for many applications of economic analyses the issues associated with climate change are tractable. In other cases it may require improved economic techniques or taking steps to ensure uncertainty is more fully addressed. Augmenting economic analysis with distribution analysis or an account of physical effects, and exploring how economic benefit and cost estimates can be incorporated into broader decision making frameworks have also been suggested. The paper concludes that there are opportunities for BCA to play a key role in informing climate change decision-making.

***Corresponding author: Fran Sussman,** ICF International, 1725 Eye Street, N.W., Washington, DC, 20006, USA, Tel.: +202 862 1200, e-mail: fsussman@rcn.com
Christopher P. Weaver and Anne Grambsch: Global Change Assessment Staff, U.S. Environmental Protection Agency, Washington, DC, USA

John Weyant*

Integrated assessment of climate change: state of the literature

Abstract: This paper reviews applications of benefit-cost analysis (BCA) in climate policy assessment at the US national and global scales. Two different but related major application types are addressed. First there are global-scale analyses that focus on calculating optimal global carbon emissions trajectories and carbon prices that maximize global welfare. The second application is the use of the same tools to compute the social cost of carbon (SCC) for use in US regulatory processes. The SCC is defined as the climate damages attributable to an increase of one metric ton of carbon dioxide emissions above a baseline emissions trajectory that assumes no new climate policies. The paper describes the three main quantitative models that have been used in the optimal carbon policy and SCC calculations and then summarizes the range of results that have been produced using them. The results span an extremely broad range (up to an order of magnitude) across modeling platforms as well as across the plausible ranges of input assumptions to a single model. This broad range of results sets the stage for a discussion of the five key challenges that face BCA practitioners participating in the national and global climate change policy analysis arenas: (1) including the possibility of catastrophic outcomes; (2) factoring in equity and income distribution considerations; (3) addressing intertemporal discounting and intergenerational equity; (4) projecting baseline demographics, technological change, and policies inside and outside the energy sector; and (5) characterizing the full set of uncertainties to be dealt with and designing a decision-making process that updates and adapts new scientific and economic information into that process in a timely and productive manner. The paper closes by describing how the BCA models have been useful in climate policy discussions to date despite the uncertainties that pervade the results that have been produced.

Keywords: benefit-cost analysis; climate change; integrated assessment; optimal carbon emissions; social cost of carbon.

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***Corresponding author: John Weyant,** Department of Management Science and Engineering, Room 260, Huang Engineering Center, Stanford University, Stanford, CA 94305-4026, USA, Phone: +1 650 723 0645, Fax: +1 650 723 3506, e-mail: weyant@stanford.edu

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Leakage, Welfare, and Cost-Effectiveness of Carbon Policy†

By Kathy Baylis, Don Fullerton, and Daniel H. Karney*

Policymakers fear that a unilateral carbon policy will reduce competitiveness, increase imports, and lead to higher carbon emissions elsewhere ("leakage"). In Fullerton, Karney, and Baylis (2012), we show that it may actually reduce emissions in other sectors ("negative leakage"). But reducing emissions in both sectors may merely reflect welfare costs of carbon policy that reduce real income and, thus, reduce consumption of both outputs. These possibilities capture the concern that unilateral carbon policy might have a high cost per global unit of carbon abated (that is, low "cost effectiveness").

Based on Harberger (1962), the two-input, two-output analytical general equilibrium model of Fullerton, Karney, and Baylis (2012) could represent two countries or two sectors of a closed economy. Each sector has some initial carbon tax or price, and the paper solves for the effect of a small increase in one sector's carbon tax on the quantity of emissions in each sector. But it does not solve for welfare effects. Here, we use the same model but derive expressions for the cost-effectiveness of a unilateral carbon tax—the welfare cost per ton of emission reduction. We show that higher leakage does not always mean lower welfare. If one sector is already taxed at a higher rate, then an increase in the other sector's tax might reduce deadweight loss from preexisting misallocations. Thus, abatement can have negative cost. The welfare cost most directly depends on the relative levels of tax in the two sectors. We show that negative leakage always corresponds to a negative income effect, but negative income effects can also arise with positive leakage. Conversely, positive leakage does not always mean positive welfare cost.

Actual carbon policy is not likely to be applied uniformly across all countries and sectors. The EU Emission Trading Scheme (EU-ETS) covers only about 40 percent of emissions (http://ec.europa.eu/clima/policies/ets/index_en.htm). In the United States, the Waxman-Markey bill proposed carbon policy primarily in the electricity sector. Metcalf and Weisbach (2009) estimate that even a very broad carbon policy can include only 80 to 90 percent of emissions, so applied carbon policy will likely leave some sectors uncovered. Raising one sector's carbon tax may have welfare costs if the other sector has no carbon tax, but, on the other hand, that other sector may face an indirect price of carbon through taxes on fossil fuels such as gasoline. Those fuels may serve as substitutes for electricity, so a new carbon tax in the electricity sector may shift consumption back somewhat from the low-taxed electricity sector into other fuels. In that case, a new carbon tax just in the electricity sector may increase welfare despite positive leakage.

This paper makes several contributions. First, we demonstrate the generality of the Fullerton, Karney, and Baylis (2012) model by showing cases where leakage can exceed 100 percent. We solve for conditions under which total emissions increase or decrease. We also solve for welfare effects, and for "cost effectiveness" (the additional welfare cost per ton of net abatement). And we explore the relationship between the sign of leakage and the sign of the effect on welfare.

In addition, we decompose the change in deadweight loss into two components. First, the unilateral increase in carbon tax worsens a production distortion, as that sector substitutes from carbon to other inputs (such as labor or capital for abatement). Second, it affects a consumption distortion, the existing misallocation between the two outputs. Depending on the other sector's preexisting carbon tax rate and carbon intensity, this consumption distortion may rise or fall.

* Baylis: Department of Agricultural and Consumer Economics, University of Illinois (e-mail: baylis@illinois.edu); Fullerton: Department of Finance, University of Illinois and NBER (e-mail: dfullert@illinois.edu); Karney: Department of Economics, University of Illinois (e-mail: dkarney2@illinois.edu). We are grateful for suggestions from Jared Carbone, Brian Copeland, Sam Kortum, Sebastian Rausch, Ian Sue Wing, and Niven Winchester.

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The Costs and Consequences of Clean Air Act Regulation of CO_2 from Power Plants[†]

By Dallas Burtraw, Josh Linn, Karen Palmer, and Anthony Paul*

The Clean Air Act (CAA) provides the regulatory framework for climate policy in the United States. In 2011, the US Environmental Protection Agency (EPA) enacted regulations for light-duty vehicles that require a 5 percent improvement in fuel economy per year and implemented preconstruction permitting for greenhouse gas emissions. The next major category to be regulated is stationary sources, beginning with electricity generators, which are responsible for nearly 40 percent of the nation's carbon dioxide (CO_2) emissions.

Most observers perceive the failure to adopt comprehensive legislation (i.e., the Waxman-Markey bill, HR 2454) in the 111th Congress as a major undoing for US climate policy. However, the United States remains positioned to achieve domestic emissions reductions in 2020 as great as would have been achieved under that legislation (Burtraw and Woerman 2013). This could enable the United States to achieve President Obama's pledge of a 17-percent reduction from 2005 emissions levels by 2020 for CO_2. Achieving the pledge hinges on the stringency and nature of regulations for the power sector.

The form of the regulations will determine their cost effectiveness. In 2013, President Obama directed EPA to move forward with regulations that, "to the greatest extent possible," allow the use of regulatory flexibility—perhaps including market-based approaches.[1]

This paper surveys the major policy approaches EPA and the states are likely to consider if markets are to be harnessed to achieve a cost-effective outcome. Each approach differs in the way it creates and allocates asset values, and this difference has important distributional and efficiency consequences. Using a simulation model of the US electricity system, we compare policies that would reduce emissions sufficiently to take the nation near the 17 percent goal for 2020. Two innovations make this modeling valuable: the model includes the first econometric estimates of the costs of improving emissions rates at existing coal boilers, and investments in energy efficiency are paid for with emissions allowance auction revenues, endogenously affecting electricity prices, investment, and system operation, and yielding dynamic demand reductions.

The policies we consider create valuable assets, and they direct those asset values to four alternative groups or uses: government, owners of fossil-fired generators, electricity consumers, and end-use energy efficiency.

We compare a cap-and-trade policy that directs auction revenue to government, and may in fact be implemented by states rather than the federal government, with a tradable performance standard that distributes the value to fossil-fuel-fired electricity generators. The standard sets a uniform emissions rate and allows generators that outperform the standard to sell credits to those that do not meet it. We compare these with two other options, following the two existing state-level cap-and-trade programs, which may serve as templates for state implementation plans. One would direct auction

* Burtraw: Resources for the Future, 1616 P Street NW, Washington, DC 20036 (e-mail: burtraw@rff.org); Linn: Resources for the Future, 1616 P Street NW, Washington, DC 20036 (e-mail: linn@rff.org); Palmer: Resources for the Future, 1616 P Street NW, Washington, DC 20036 (e-mail: palmer@rff.org); Paul: Resources for the Future, 1616 P Street NW, Washington, DC 20036 (e-mail: paul@rff.org). This research was supported by Mistra's Indigo Program and RFF's Center for Climate and Electricity Policy. The authors appreciate comments from Gilbert Metcalf and assistance from Sophie Pan and Samantha Sekar.

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[1] http://www.whitehouse.gov/the-press-office/2013/06/25/presidential-memorandum-power-sector-carbon-pollution-standards.

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convective precipitation likely to increase more rapidly than stratiform precipitation[8,9]. However, other changes — such as shifts in large-scale circulation patterns — may have different responses to climate change in different seasons[10], and this can also influence trends in extreme precipitation intensity, as observed here. Simulating the combined effect of all of these processes remains a major challenge in climate modelling. Although some recent modelling studies have emphasized sub-daily precipitation[11], more work is needed to understand the dominant processes that govern changes in extreme precipitation at both short (sub-daily and sub-hourly) and long timescales.

Given the fundamental relationship between catchment size, the duration of an extreme precipitation event and flood magnitude[12], the finding that extreme precipitation is changing at different timescales has potentially surprising implications for flood risk. Our results show that different or even opposing trends in flood risk are possible within a single geographic region, such as neighbouring catchments of different sizes, or even smaller sub-catchments within the same larger basin. This will be of interest to those involved in land-use planning, water infrastructure design (for example dams, levees, bridges and storm-water drainage networks), floodplain management, emergency response, as well as to the insurance industry. ❐

References
1. Boucher, O. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 7 (IPCC, Cambridge Univ. Press, 2013).
2. Westra, S. *et al. Rev. Geophys.* **52,** 522–555 (2014).
3. Field, C. B. *et al.* (eds) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, Cambridge Univ. Press, 2012).
4. Westra, S. & Sisson, S. *J. Hydrol.* **406,** 119–128 (2011).
5. Westra, S. *et al. J. Clim.* **26,** 3904–3918 (2013).
6. Delworth, T. L. & Zeng, F. *Nature Geosci.* **7,** 583–587 (2014).
7. *Summary of Climate Change Impacts Sydney Region* (Department of Environment and Climate Change New South Wales, 2008); http://www.environment.nsw.gov.au/resources/climatechange/08519Sydney.pdf
8. Lenderink, G. & Van Meijgaard, E. *Nature Geosci.* **1,** 511–514 (2008).
9. Berg, P., Moseley, C. & Haerter, J. O. *Nature Geosci.* **6,** 181–185 (2013).
10. Grose, M. *et al. Clim. Dynam.* **39,** 445–459 (2012).
11. Kendon, E. J. *et al. Nature Clim. Change* **4,** 570–576 (2014).
12. Brutsaert, W. *Hydrology — An Introduction* (Cambridge Univ. Press, 2005).

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Additional information
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Feifei Zheng, Seth Westra* and Michael Leonard
School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, South Australia 5005, Australia.
*e-mail: seth.westra@adelaide.edu.au

CORRESPONDENCE:

IAMs and peer review

To the Editor — Integrated assessment models (IAMs) have provided the bulk of the evidence relied on by prominent documents — such as the Stern Report[1] and the contributions of Working Group III to the IPCC Assessment Reports[2,3] — as well as numerous research articles on the economics of climate change mitigation and related issues. I am concerned, however, that many published IAM-based research articles fail to adequately explain the basis for their findings, and do not justify these findings carefully based on sound scientific and logical argumentation, analysis, and data presented in the article itself (or in published appendices). Often the details of how the IAMs were used to derive the basic results are not described, meaning that reviewers cannot credibly assess the reliability of the results.

One major flaw of most, if not all, peer reviews of IAM-based research reports is that the models relied upon have not been reviewed in themselves. And yet such articles cannot be adequately reviewed without carefully critiquing the underlying models. All too often the original models, and subsequent versions, have never been formally peer reviewed publicly. Due to these shortcomings, even the recent 'model intercomparison projects'[4] are, I would argue, of limited value.

Because economics claims to be a science, and because economists have developed many different IAMs, peer reviewers of IAM-based research articles should, in my view, assess: (1) the theory behind each model in light of model's intended purpose; (2) the structure of the model to determine if the theory was properly implemented; (3) the way in which various structural parameters were estimated based on historical data; and (4) the way in which the values of various input parameters were estimated or derived, especially those for the future. The last point is a particular problem because many IAM-based studies involve very long-term, multi-decadal projections. In addition, I believe that peer reviewers must especially assess how the model is being used in relation to the particular research questions being addressed, and what sensitivity analyses have been performed that might illuminate the answers to these questions. If any of these steps are skipped, then confidence in the reported findings is reduced. Of course, if some of these steps have been undertaken for previously published articles using the same IAM, and if the model has not significantly changed since these reviews were completed, then some of the above steps could be deemed to be complete prior to the current review. It would be helpful in this regard if past reviews of the particular IAM were made available in some format. But this is almost never done.

In 2013, the IAM Consortium — which was set up at the request of the IPCC after the Fourth Assessment Report and of which I am a member — set up scientific working groups intending to establish community-wide standards on IAM documentation and the inclusion of key input assumptions in research publications. There has been little or no progress since. It is my contention that this situation should be rectified, so as to usher in a new era for peer reviews in this field. ❐

References
1. Stern, N. *The Economics of Climate Change – The Stern Review* (Cambridge Univ. Press, 2007).
2. IPCC *Climate Change 2007: Mitigation of Climate Change* (eds Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. & Meyer, L.A.) (Cambridge Univ. Press, 2007).
3. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).
4. Rosen, R. A. *Technol. Forecast. Soc. Change* http://dx.doi.org/10.1016/j.techfore.2015.01.019 (2015).

Richard A. Rosen
Tellus Institute, 11 Arlington Street, Boston, Massachusetts 02116-3411, USA. e-mail: rrosen@tellus.org

CORRESPONDENCE:

Long history of IAM comparisons

To the Editor— We agree with the point made in a recent Editorial in this journal[1] that the assumptions behind models of all types, including integrated assessment models (IAMs), should be as transparent as possible. However, it is incorrect to imply that the IAM community is just "now emulating the efforts of climate researchers by instigating their own model inter-comparison projects."

In fact, model comparisons for integrated assessment and climate models followed a remarkably similar trajectory. Early general circulation model (GCM) comparison efforts[2] evolved to the first Atmospheric Model Inter-comparison Project (AMIP), which was initiated in the early 1990s[3]. Atmospheric models developed into coupled atmosphere–ocean models (AOGCMs) and results from the first Coupled Model Inter-Comparison Project (CMIP1) became available about a decade later[4].

Results of first energy model comparison exercise, conducted under the auspices of the Stanford Energy Modeling Forum, were published in 1977[5]. A summary of the first comparison focused on climate change was published in 1993[6]. As energy models were coupled to simple economic and climate models to form IAMs, the first comparison exercise for IAMs (EMF 14; https://emf.stanford.edu/projects) was initiated in 1994, and IAM comparison exercises have been ongoing since this time[7–10] — and were recently assessed in the latest IPCC report[11] — including a publicly accessible database of scenarios (https://secure.iiasa.ac.at/web-apps/ene/AR5DB). ❐

References
1. *Nature Clim. Change* **5**, 81 (2015).
2. *Understanding Climatic Change* Appendix B (National Academy of Sciences, 1975).
3. Gates, W. L. *et al. Bull. Am. Meteorol. Soc.* **80**, 29–55 (1999).
4. Covey, C. *et al. Clim. Dynam.* **16**, 775–787 (2000).
5. EMF Working Group *Energy and the Economy: EMF Report 1* (Stanford Univ., 1977).
6. Gaskins, D. W. Jr & Weyant, J. P. *Am. Econ. Rev.* **83**, 318–323 (1993).
7. Kriegler, E. *et al. Technol. Forecast. Soc. Change* **90**, 24–44 (2015).
8. Calvin, K. L. *et al. Energy Econ.* **34**(suppl. 3), S251–S260 (2012).
9. Edenhofer, O. *et al. Energy J.* **31**(special issue), 11–48 (2010).
10. Luderer, G. *et al. Climatic Change* **114**, 9–37 (2012).
11. Clarke L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).

Steven J. Smith[1]*, Leon E. Clarke[1], James A Edmonds[1], Jiang Kejun[2], Elmar Kriegler[3], Toshihiko Masui[4], Keywan Riahi[5], Priyadarshi R. Shukla[6], Massimo Tavoni[7], Detlef P. van Vuuren[8,9] and John P. Weyant[10]
[1]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland 20740, USA. [2]Energy Research Institute, B1505, Guohong Building, Jia.No.11, Muxidibeili, Xicheng District, Beijing 100038, China. [3]Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany. [4]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan. [5]International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria. [6]Indian Institute of Management, Vastapur, Ahmedabad 380015, India. [7]Fondazione Eni Enrico Mattei (FEEM), Corso Magenta 63, 20123 Milano, Italy. [8]PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, the Netherlands. [9]Faculty of Geosciences, Utrecht University, 3584 CS Utrecht, the Netherlands. [10]Department of Management Science and Engineering, Stanford University, Stanford, California 94305, USA.
*e-mail: ssmith@pnl.gov

CORRESPONDENCE:

Strategies for changing the intellectual climate

To the Editor— Castree *et al.*[1] are correct that a 'single, seamless concept of integrated knowledge' cannot do justice to the diversity of meanings that need to be brought to bear in addressing the challenges of global environmental change. We also agree with them that environmental social sciences and humanities (ESSH) can make important contributions to global environmental change (GEC) science. However, their charge that we ignore the full range of anthropological contributions to understanding of climate change reflects a misreading of our recent Perspective[2] in this journal, as we only attempted to discuss a few exemplary strands of the many contributions from anthropology to a richer understanding of climate change (for a more detailed discussion, see our forthcoming edited volume[3]).

Secondly, Castree *et al.* suggest that we are reinforcing the status quo in GEC science and 'pulling our punches' by using terms common in Earth systems science (such as system and mechanism). Our use of such terms reflected a strategy to use familiar language to raise awareness of anthropological contributions little known to most GEC scientists, along the lines of the 'clumsy solutions' proposed by anthropologist Steven Rayner[4]. Rayner calls for these solutions to 'wicked problems' such as climate change — problems marked by deep underlying conflicts about the nature of the problem itself — because they can allow different actors to work together without sharing ethical or epistemological principles. We agree with Castree *et al.* that other strategies are possible, but not that theirs is the only route to a wider dialogue.

Castree *et al.* focus on three texts to illustrate how GEC scientists evoke the notion of seamless, totalizing knowledge. They single out the use of terms such as 'integration' in discussions of knowledge to

COMMENTARY:

Pricing climate risk mitigation

Joseph E. Aldy

Adaptation and geoengineering responses to climate change should be taken into account when estimating the social cost of carbon.

At the September 2014 United Nations Climate Summit, 73 countries and more than 1,000 companies advocated pricing carbon[1]. Economists have long called for pricing carbon to reflect the social damages associated with the impacts of carbon dioxide emissions on the global climate[2,3]. Such an approach generally reflects the polluter pays principle — as elaborated in the 1992 Rio declaration on environment and development, with its emphasis on the use of economic instruments to internalize environmental costs[4]. Scholars have also called for the organization of international negotiations around agreement on a carbon price to provide the basis for emission commitments[5,6].

The meaning of carbon pricing

For some policymakers, setting a price on carbon that reflects the cost of carbon pollution can inform the 'objective' of climate policy. For example, the US government uses an estimate of the social cost of carbon (SCC) — the present value of monetized damages associated with an incremental ton of carbon dioxide emissions — to evaluate standards for fuel economy, appliance efficiency and carbon emissions[7]. As some laws require regulations to reflect a weighting of benefits and costs, the application of the SCC could determine the ambition of energy and climate policies.

For other policymakers, pricing carbon is an 'instrument' of climate policy — such as carbon dioxide cap-and-trade programmes or a carbon tax. For example, the European Union emissions trading scheme and the British Columbia carbon tax impose a price that carbon dioxide-emitters must bear. Of course, these two interpretations can be mutually reinforcing. In a benefit–cost framework, a policy that maximizes net social benefits would equate the SCC with the price borne by emitters under a tax or cap-and-trade instrument[8].

Whether the SCC determines the objective of policy, informs the design of a pricing instrument, or serves as a focal point in international negotiations, it will play an important role in the future of climate change policy. The social damages of carbon emissions will depend on the impacts of a warming world, such as sea-level rise, extreme weather events and changes in agricultural productivity, as well as potential catastrophic harms, migration, conflict and so on[9]. The SCC will also vary with alternative efforts to mitigate climate change risks, such as adaptation and geoengineering. Thus, it is important to conceptualize the SCC in the context of the full suite of risk management policies for climate change.

Managing risks posed by climate change

Policymakers, individuals and businesses can use three general approaches to mitigate the risks posed by climate change. First, they can halt the atmospheric accumulation of greenhouse gases, thereby preventing the problem through emission abatement. Second, they can avoid some climate change impacts by making investments in adaptation and resilience. Third, they can attempt to 'fix' the problem through geoengineering, such as solar radiation management strategies.

This multipronged approach to mitigating climate risk has emerged only recently in the debate over climate change policy. In the 1990s, international and domestic climate change policy focused almost exclusively on emission abatement. In the early 2000s, adaptation joined emission abatement in multilateral negotiations as well as development policy. In recent years, scholars have raised the prospect of geoengineering paired with emission abatement to avoid potentially catastrophic climate change[10–12]. Putting a price on carbon for emission abatement that fails to account for adaptation and geoengineering risks could leave too few resources for these options, which have potentially high returns in reducing climate change damages.

Role of adaptation and geoengineering

Pricing carbon within a comprehensive risk management framework requires continued work and advances in our understanding of climate change damages. Scholars from an array of disciplines have raised questions about the damage functions in the integrated assessment models that generate SCC estimates[9,13,14]. Improving the knowledge base on climate change impacts is a necessary foundation for evaluating the risk mitigation impacts of emission abatement, adaptation and geoengineering.

The status quo integrated assessment model approach produces an estimate of SCC without consideration of geoengineering and typically with incomplete or ad hoc attempts to represent adaptation[15]. Of the more than 400,000 SCC estimates produced by the US government in its 2013 report[15], 160 scenarios had a SCC in excess of US$1,000 per ton — or nearly US$10,000 in annual climate damages per US household — for its residential energy consumption. It is difficult to imagine that if the world were in such a dire state there would be no increase in adaptation investment or geoengineering deployment to offset at least some of these impacts.

Many individuals and businesses have strong incentives to mitigate their exposure to risks related to climate change. If the impacts of climate change become more severe, then they will increase their private adaptation investments. Moreover, governments are likely to increase outlays for resilience and adaptation if climate risks become more pronounced.

Adaptation will not fully offset the increase in damages, but it is likely to offset some climate change risk. As a result, the integrated assessment framework for evaluating the damages of an incremental emission of carbon dioxide should be expanded to include an 'adaptation response function'. Such a function (or system of functions) would represent how adaptation actions by governments and private agents respond to climate change, how adaptation affects the residual damages associated with another ton of carbon dioxide in the air, and how much this adaptation costs. This adaptation response

ENVIRONMENTAL ECONOMICS

Using and improving the social cost of carbon

Regular, institutionalized updating and review are essential

By William Pizer,[1,2]*† Matthew Adler,[1] Joseph Aldy,[2,3] David Anthoff,[4] Maureen Cropper,[2,5] Kenneth Gillingham,[6] Michael Greenstone,[7] Brian Murray,[1] Richard Newell,[1,2] Richard Richels,[8] Arden Rowell,[9] Stephanie Waldhoff,[10] Jonathan Wiener[1,2]

The social cost of carbon (SCC) is a crucial tool for economic analysis of climate policies. The SCC estimates the dollar value of reduced climate change damages associated with a one-metric-ton reduction in carbon dioxide (CO_2) emissions. Although the conceptual basis, challenges, and merits of the SCC are well established, its use in government cost-benefit analysis (CBA) is relatively new. In light of challenges in constructing the SCC, its newness in government regulation, and the importance of updating, we propose an institutional process for regular SCC review and revision when used in government policy-making and suggest how scientists might contribute to improved SCC estimates.

POLICY

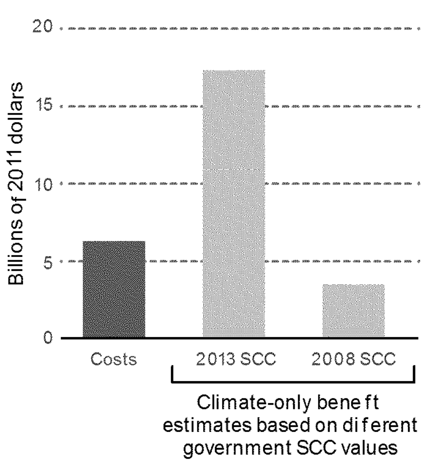
Although regulations issued by U.S. federal agencies have been subject to CBA for four decades, those analyses largely ignored economic benefits of carbon reduction until a federal court held in 2008 that carbon emission reductions have nonzero value. After a brief period during which different U.S. agencies used different SCC numbers, an interagency working group established a single set of government-wide values in 2009 and 2010, with an update in 2013 (*1*).

Such updates arise because the science, impact estimates, and socioeconomic models used to develop the SCC continue to evolve, as do expert opinions about how it should be synthesized. The results for CBA are consequential (see the graph). Using the most recent central value of interagency SCC estimates, a proposed U.S. rule on emissions from existing power plants would pass a CBA on climate benefits alone (*2*); using the central value SCC from a single agency in 2008 (*3*), it would not.

Estimating the SCC in a particular year, say 2015, involves four steps: (i) projecting a future path of global greenhouse gas (GHG) emissions; (ii) translating this emissions path, along with an alternative that adds 1 ton in 2015, into alternate scenarios of climate change; (iii) estimating physical impacts of these climate changes on humans and ecosystems; and (iv) monetizing these impacts and discounting future monetary damages back to 2015. The SCC is the difference in damage valuations with and without the extra ton of CO_2 in 2015.

Integrated assessment models [IAMs; e.g., DICE (*4*), FUND (*5*), and PAGE (*6*)], perform all four steps. Underlying step (i) are assumptions about future climate change policies and their effects on GHG emissions and about population, GDP growth, and technology. In step (ii), a simplified representation of the climate system translates emissions to metrics of climate change (e.g., change in global average temperature). Steps (iii) and (iv) require a damage function that relates climate change metrics to climate impacts and to valuations. Valuation of impacts often aggregates and/or extrapolates detailed climate impact studies and relies on population and economic assumptions from step (i) to project the level of human and economic activity exposed to these impacts in the future.

Costs and benefits of emissions reductions



Benefits of regulations vary. Estimated costs and climate change benefits of emission reductions in 2020 from proposed U.S. power plant regulations using 2008 (*3*) and 2013 (*2*) government SCC estimates. Estimates from table 18 in (*2*) using a 3% discount rate averaged over state and regional approaches. SCC estimate from table V-3 in (*3*), rising 2.4% per year to $8.67 in 2020, multiplied by avoided emissions estimates averaged over state and regional approaches from table 10 in (*2*), and inflation adjusted using the implicit GDP price index from the U.S. Bureau of Economic Analysis.

DIFFICULT CHOICES. Constructing an SCC for government CBA requires specific choices, beginning with the selection of which IAMs to include. Models vary in terms of breadth of use, degree of public access and available peer review, and incorporation of latest scientific results. New IAMs may emerge. How should a government select among models? Should selection evolve over time? Should models be weighted? If so, how?

Next, one must choose what, if any, assumptions to harmonize across models. Such assumptions may be important for consistency between the SCC and other elements of a government CBA, to reflect important uncertainties, or to address possibly outdated assumptions.

This harmonization requires more tough choices. For example, the SCC will measure incremental policy benefits relative to a baseline or range of baselines, which must be explicitly selected. One must decide whether emissions are forecast on the basis of an ambitious climate policy (such as the scenario in which polluters are already forced to pay the estimated SCC), a scenario where only policies already on the books remain in place, or something in between.

There are also credible differences on analytic and ethical grounds regarding the appropriate discount rate. Previous government guidance for CBA suggested discount rates of 3 and 7% for most projects, with possibly lower rates for phenomena (like climate change) with important intergenerational effects (*7*). Such differences have enormous implications; federal SCC estimates tripled as the discount rate changes from 5 to 3% (*1*). For practical CBA, it is important to have distinct SCC estimates for different discount rates that can be paired with cost estimates based on a particular discount rate(s).

Each IAM will have its own internal discount rate determined by model parameters and socioeconomic forecasts. Low discount rates typically follow from low economic growth (*8*), and economic growth is tied to climate impacts. Given this connection, how problematic is it to impose a discount rate in the SCC that is different from the rate used within the IAM itself?

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From My Perspective

Critical review of: "Making or breaking climate targets—the AMPERE study on staged accession scenarios for climate policy" (TFSC 17862)

Richard A. Rosen

Tellus Institute, 11 Arlington St., Boston, MA 02116, USA

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This critical review of the integrated assessment modeling (IAM) research underlying the AMPERE study is also relevant to many other IAM-based model comparison papers. One of the main symptoms of the serious methodological problems of these studies is that the results produced by different models for what are portrayed as the "same" scenarios differ quite substantially from each other. While the authors of the AMPERE study correctly raise the important question of whether these differences are due primarily to differences in model structures, or to differences in the sets of input assumptions for the "same" scenario used by different research teams, they never address this question in a logically systematic and credible way. In fact, they cannot and do not arrive at an answer, since each modeling team generally relies on a single but different set of most input assumptions for the same scenario. Finally, the research teams involved in the AMPERE project, and other similar projects, fail to understand the fundamental impossibility of forecasting net mitigation costs or benefits over the long run given both the practical and deep uncertainties implicit in both the equations comprising these IAMs, and the input assumptions on which they rely.

1. Introduction

The AMPERE project was a major EU-funded research effort to try to determine the economics and, therefore, the desirability of "staged accession" scenarios to mitigate climate change at the global level through 2100, with a focus on the European Union as the key actor. The results of this research are presented in the TFSC article under review here (Kriegler et al., 2014). Staged accession scenarios appear to involve various regions of the world taking action to mitigate climate change in different ways and at different times, rather than collectively at the same time. This project produced several mitigation scenarios for analysis and comparison to a reference policy case. The details of these mitigation scenarios are not important for our critical analysis here. Instead, what is important is the project's focus on the differences in the long-run economic results for different mitigation scenarios when compared to the reference policy case, especially the results for the EU and China. These economic results include the present value of the GDP and other economic costs and benefits computed by the models, as well as the cost of carbon prices computed in different scenarios.

The purpose of this critical review, which is unusual within the literature on the economics of mitigating climate change, is to try to enumerate the major weaknesses of the AMPERE project in attempting to apply credible methodologies for analyzing the results of this type of modeling study. One goal of this critique is to encourage the various integrated assessment modeling teams around the world to reconsider their research priorities in light of the types of problems identified here. If integrated assessment models of the types utilized in this major EU project are going to be used in the future to assist policy makers, the ways they are used, as well as the models themselves, will require major modifications.[1] And while the issue of TFSC in which this overview of the AMPERE study was published also contains many other articles on related topics, I

[1] This paper will not address the model flaws, some of which are addressed in reference 2, and other papers referenced in that paper.

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The economics of mitigating climate change: What can we know?

Richard A. Rosen [a],*, Edeltraud Guenther [b]

[a] Tellus Institute, 11 Arlington St., Boston, MA 02116, USA
[b] Technische Universitaet Dresden, 01069 Dresden, Germany

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abstract

The long-term economics of mitigating climate change over the long run has played a high profile role in the most important analyses of climate change in the last decade, namely the Stern Report and the IPCC's Fourth Assessment. However, the various kinds of uncertainties that affect these economic results raise serious questions about whether or not the net costs and benefits of mitigating climate change over periods as long as 50 to 100 years can be known to such a level of accuracy that they should be reported to policymakers and the public. This paper provides a detailed analysis of the derivation of these estimates of the long-term economic costs and benefits of mitigation. It particularly focuses on the role of technological change, especially for energy efficiency technologies, in making the net economic results of mitigating climate change unknowable over the long run.

Because of these serious technical problems, policymakers should not base climate change mitigation policy on the estimated net economic impacts computed by integrated assessment models. Rather, mitigation policies must be forcefully implemented anyway given the actual physical climate change crisis, in spite of the many uncertainties involved in trying to predict the net economics of doing so.

1. Introduction

Over the past 10 years, dozens of articles, reports, and papers have addressed the economics of mitigating climate change. As one might expect, both the quantitative results and the computational models that produced them have changed somewhat, though not dramatically, over time. During that decade, the negative impacts of climate change on the physical world have become more frequent, and most proposed climate mitigation targets have become more stringent. Today, the generally accepted temperature target, to which most governments agree, would limit the increase in temperature due to greenhouse gas emissions derived from human-related activities to 2 °C, relative to pre-industrial times, by 2100. As years pass, the time remaining to meet that target decreases. Furthermore, the costs of mitigating climate change will tend to increase if mitigation is delayed and if future energy technology costs and performance characteristics follow current forecasts, although forecasts of some of these important parameters have changed significantly over the last 10 years. Of course, the actual prices of the fossil fuels that climate change mitigation would displace have also changed in this time, even more than the long-run forecasts of future fuel prices, raising interesting questions about the current forecasts.

The best and most recent comprehensive reviews of the economics of mitigating climate change appeared in the Working Group III report of the Fourth Climate Assessment of the Intergovernmental Panel on Climate Change (IPCC) and the 6, sponsored by the British government [1,2]. Since both reports were published in 2007, the underlying research would have been undertaken prior to or during 2006, making both studies somewhat out-of-date already. However,

* Corresponding author.
E-mail addresses: rrosen@tellus.org (R.A. Rosen), edeltraud.guenther@tu-dresden.de (E. Guenther).

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John Weyant*

Integrated assessment of climate change: state of the literature

Abstract: This paper reviews applications of benefit-cost analysis (BCA) in climate policy assessment at the US national and global scales. Two different but related major application types are addressed. First there are global-scale analyses that focus on calculating optimal global carbon emissions trajectories and carbon prices that maximize global welfare. The second application is the use of the same tools to compute the social cost of carbon (SCC) for use in US regulatory processes. The SCC is defined as the climate damages attributable to an increase of one metric ton of carbon dioxide emissions above a baseline emissions trajectory that assumes no new climate policies. The paper describes the three main quantitative models that have been used in the optimal carbon policy and SCC calculations and then summarizes the range of results that have been produced using them. The results span an extremely broad range (up to an order of magnitude) across modeling platforms as well as across the plausible ranges of input assumptions to a single model. This broad range of results sets the stage for a discussion of the five key challenges that face BCA practitioners participating in the national and global climate change policy analysis arenas: (1) including the possibility of catastrophic outcomes; (2) factoring in equity and income distribution considerations; (3) addressing intertemporal discounting and intergenerational equity; (4) projecting baseline demographics, technological change, and policies inside and outside the energy sector; and (5) characterizing the full set of uncertainties to be dealt with and designing a decision-making process that updates and adapts new scientific and economic information into that process in a timely and productive manner. The paper closes by describing how the BCA models have been useful in climate policy discussions to date despite the uncertainties that pervade the results that have been produced.

Keywords: benefit-cost analysis; climate change; integrated assessment; optimal carbon emissions; social cost of carbon.

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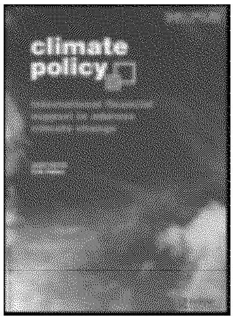
***Corresponding author: John Weyant,** Department of Management Science and Engineering, Room 260, Huang Engineering Center, Stanford University, Stanford, CA 94305-4026, USA, Phone: +1 650 723 0645, Fax: +1 650 723 3506, e-mail: weyant@stanford.edu



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Incorporating 'catastrophic' climate change into policy analysis

Elizabeth Kopits[a], Alex Marten[a] & Ann Wolverton[a]

[a] National Center for Environmental Economics, US Environmental Protection Agency (EPA), 1200 Pennsylvania Avenue, NW MC 1809T, Washington, DC 20460, USA

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What Do We Learn from the Weather? The New Climate–Economy Literature

Melissa Dell, Benjamin F. Jones, and Benjamin A. Olken*

A rapidly growing body of research applies panel methods to examine how temperature, precipitation, and windstorms influence economic outcomes. These studies focus on changes in weather realizations over time within a given spatial area and demonstrate impacts on agricultural output, industrial output, labor productivity, energy demand, health, conflict, and economic growth, among other outcomes. By harnessing exogenous variation over time within a given spatial unit, these studies help credibly identify (i) the breadth of channels linking weather and the economy, (ii) heterogeneous treatment effects across different types of locations, and (iii) nonlinear effects of weather variables. This paper reviews the new literature with two purposes. First, we summarize recent work, providing a guide to its methodologies, datasets, and findings. Second, we consider applications of the new literature, including insights for the "damage function" within models that seek to assess the potential economic effects of future climate change. (*JEL* C51, D72, O13, Q51, Q54)

1. *Introduction*

The idea that climate may substantially influence economic performance is an old one, featuring prominently in the writings of the Ancient Greeks, in Ibn Khaldun's fourteenth-century *Muqaddimah* (Gates 1967), and during the Enlightenment, when Montesquieu argued in *The Spirit of Laws* (1748) that an "excess of heat" made men "slothful and dispirited." To the extent that climatic factors affect economically relevant outcomes, whether agricultural output, economic growth, health, or conflict, a careful understanding of such effects may be essential to the effective design of contemporary economic policies and institutions. Moreover, with global temperatures expected to rise substantially over the next century, understanding these relationships is increasingly important for assessing the "damage function" that is central to estimating the potential economic implications of future climate change.

A basic challenge in deciphering the relationship between climatic variables and economic activity is that the spatial variation in climate is largely fixed. Canada is colder

* Dell: Harvard University. Jones: Northwestern University. Olken: Massachusetts Institute of Technology. We thank Marshall Burke, Janet Currie, Michael Greenstone, Solomon Hsiang, Elizabeth Moyer, Robert Pindyck, Richard Schmalensee, Susan Solomon, and five anonymous referees for helpful comments.

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A RAPID ASSESSMENT MODEL FOR UNDERSTANDING THE SOCIAL COST OF CARBON*

STEPHEN C. NEWBOLD†, CHARLES GRIFFITHS, CHRIS MOORE, ANN WOLVERTON and ELIZABETH KOPITS

U.S. EPA, National Center for Environmental Economics
EPA West Building — 4316T, 1301 Constitution Avenue NW
Washington, DC 20460, USA
†*newbold.steve@epa.gov*

Published 20 March 2013

The "social cost of carbon" (SCC) is the present value of the stream of future damages from one additional unit of carbon emissions in a particular year. This paper develops a rapid assessment model for the SCC. The model includes the essential ingredients for calculating the SCC at the global scale and is designed to be transparent and easy to use and modify. Our goal is to provide a tool to help analysts and decision-makers quickly explore the implications of various modeling assumptions for the SCC. We use the model to conduct sensitivity analyses over some of the key input parameters, and we compare estimates of the SCC under certainty and uncertainty in a Monte Carlo analysis. We find that, due to the combined effects of uncertainty and risk aversion, the certainty-equivalent SCC can be substantially larger than the expected value of the SCC. In our Monte Carlo simulation, the certainty-equivalent SCC is more than four times larger than the expected value of the SCC, and we show that this result depends crucially on how the uncertain preference parameters are handled. We also compare the approximate present value of benefits estimated using the SCC to the exact value of compensating variation in the initial period for a wide range of hypothetical emission reduction policies.

Keywords: Climate change; integrated assessment model; social cost of carbon; climate sensitivity.

1. Introduction

The "social cost of carbon" (SCC) is a commonly estimated measure of the economic benefits of reductions in emissions of carbon dioxide (CO_2), the predominant anthropogenic greenhouse gas (e.g., Tol, 2005, 2008; Nordhaus, 2008; Hope, 2006, 2008; Anthoff *et al.*, 2009a,b). The SCC represents the present value of the stream of future damages from an incremental increase in CO_2 emissions in a particular year, and therefore it also represents the marginal benefit of emissions reductions. The SCC is intended to be a comprehensive measure of damages, including the impacts of global warming on agricultural productivity and human health; loss of property and

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Harvard Environmental Economics Program

DEVELOPING INNOVATIVE ANSWERS TO TODAY'S COMPLEX ENVIRONMENTAL CHALLENGES

March 2015
Discussion Paper 15-62

The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

Gilbert Metcalf
Tufts University

James Stock
Harvard University

HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

heep@harvard.edu
http://heep.hks.harvard.edu

ENVIRONMENTAL ECONOMICS

Determining Benefits and Costs for Future Generations

The United States and others should consider adopting a different approach to estimating costs and benefits in light of uncertainty.

K. Arrow,[1] M. Cropper,[2,3*] C. Gollier,[4] B. Groom,[5] G. Heal,[6] R. Newell,[3,7,8] W. Nordhaus,[9] R. Pindyck,[10] W. Pizer,[3,11] P. Portney,[3,12] T. Sterner,[3,13] R. S. J. Tol,[14,15] M. Weitzman[16]

In economic project analysis, the rate at which future benefits and costs are discounted relative to current values often determines whether a project passes the benefit-cost test. This is especially true of projects with long time horizons, such as those to reduce greenhouse gas (GHG) emissions. Whether the benefits of climate policies, which can last for centuries, outweigh the costs, many of which are borne today, is especially sensitive to the rate at which future benefits are discounted. This is also true of other policies, e.g., affecting nuclear waste disposal or the construction of long-lived infrastructure.

A declining discount rate (DDR) schedule, as used by the governments of France and the United Kingdom (*1*, *2*), means that all benefits and costs occurring in a given year are discounted at the same rate, but this rate declines over time. In contrast, the United States and other countries use discount rates that are constant over time; a lower constant discount rate is sometimes used to evaluate projects that affect future generations. We summarize the arguments in favor of using a DDR schedule and discuss the problems in using different constant discount rates to evaluate inter- and intragenerational benefits. The use of a DDR schedule would avoid these problems.

What Does the Discount Rate Represent?

There are two rationales for discounting future benefits, one consumption- and the other investment-based. The consumption rate of discount reflects the rate at which society is willing to trade consumption in the future for consumption today. Basically, we place a lower value on the consumption of future generations, because we assume that future generations will be wealthier than we are and that the utility people receive from an extra dollar of consumption declines as their level of consumption increases. To illustrate, if per capita consumption grows at 1.3% per year, in 200 years it will be more than13 times today svalue. So a dollar of consumption received 200 years from now will therefore be worth less than it is today (*3*).

The investmentapproach says that, as long as the rate of return to investment is positive, we need to invest less than a dollar today to obtain a dollar of benefits in the future. Under the investment approach, the discount rate is the rate of return on investment. If there were no distortions (e.g., taxes) or inefficiencies in markets, the consumption rate of discount would equal the rate of return on investment. There are, however, many reasons why the two may differ (*4*), which is why the U.S. Office of Management and Budget (OMB) requires projects involving intragenerational benefits and costs to be evaluated twice, once by using a constant discount rate of 3% to approximate the consumption rate of discount and, separately, by using a discount rate of 7% the real, pretax average return on private investment. For regulations with important intergenerational benefits or costs, OMB advises analysts to consider an additional lower but positive discount rate (*5*).

Using a constant discount rate for intergenerational benefits and costs that is lower than the rate used to evaluate intragenerational benefits and costs can lead to inconsistencies in decision-making. In a recent regulatory impact analysis of Corporate Average Fuel Economy standards for motor vehicles (*6*), benefits associated with reduced GHG emissions were discounted at a lower rate than fuel savings associated with the proposed standards. This resulted in benefits occurring in the same year being discounted at different rates. This is clearly inappropriate (*7*). Consistency in decision-making requires that the same discount rate must be applied to all certain benefits and costs that occur in the same year, irrespective of whether the project has intra- or intergenerational consequences. With a DDR schedule, benefits and costs in a given year are discounted at the same rate, but the rate declines over time.

Present value of a cash flow of $1000 received after t years

t	Value ($) of $1000 at a discount rate of				Certainty equivalent (%)
	1%	4%	7%	Equally likely 1% or 7% expected value	
1	990.05	960.79	932.39	961.22	3.94
10	904.84	670.32	496.59	700.71	3.13
50	606.53	135.34	30.20	318.36	1.28
100	367.88	18.32	0.91	184.40	1.02
150	223.13	2.48	0.03	111.58	1.01
200	135.34	0.34	0.00	67.67	1.01
300	49.79	0.01	0.00	24.89	1.01
400	18.32	0.00	0.00	9.16	1.01

Present value of a cash flow of $1000 received after *t* years. Expected value is the average of values from the 1% and 7% columns.

Why Might the Discount Rate Decline?

Uncertainty about future discount rates leads to a DDR schedule (*8*). This can be illustrated by a simple example. Suppose we wish to discount $1000 received *t* years from now to the present. The net present value (NPV) of $1000 = $1000*exp(*rt*), where *r* is the discount rate. If the discount rate is 4%, the NPV of $1000 received in 100 years is $18.32 (see the table).

But future discount rates are inherently uncertain. Suppose that we think the interest rate is equally likely to be 1% or 7% in 100 years. We evaluate the NPV using its expected value (*9*), averaging the

[1]Stanford University, Stanford, CA 94305, USA. [2]University of Maryland, College Park, MD 20742, USA. [3]Resources for the Future, Washington, DC 20036, USA. [4]Toulouse School of Economics, 31000 Toulouse, France. [5]London School of Economics, London WC2A 2AE, UK. [6]Columbia Business School, New York, NY 10027, USA. [7]Nicholas School of the Environment, Duke University, Durham, NC 27708, USA. [8]National Bureau of Economic Research, Cambridge, MA 02138, USA. [9]Cowles Foundation, Yale University, New Haven, CT 06511, USA. [10]Sloan School of Management, Massachusetts Institute of Technology, Newton, MA 02159, USA. [11]Sanford School of Public Policy, Duke University, Durham, NC 27708, USA. [12]University of Arizona, Tucson, AZ 85721, USA. [13]University of Gothenburg, SE-405 30 Gothenburg, Sweden. [14]Univeristy of Sussex, Sussex BN1 9SL, UK. [15]Institute for Environmental Studies and Department of Economics, Vrije Universiteit, 1081 HV Amsterdam, Netherlands. [16]Harvard University, Cambridge, MA 02138, USA.

*Correspondingauthor: cropper@rff.org

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Should Governments Use a Declining Discount Rate in Project Analysis?

Kenneth J. Arrow*, Maureen L. Cropper[y], Christian Gollier[z], Ben Groom[§], Geoffrey M. Heal[ffi], Richard G. Newell[k], William D. Nordhaus[#], Robert S. Pindyck**, William A. Pizer[yy], Paul R. Portney[zz], Thomas Sterner[§§], Richard S. J. Tol[fiffi], and Martin L. Weitzman[kk]

Introduction

In project analysis, the rate at which future benefits and costs are discounted often determines whether a project passes the benefit-cost test. This is especially true of projects that have long time horizons, such as those aimed at reducing greenhouse gas (GHG) emissions. In the case of

*Stanford University; e-mail: arrow@stanford.edu.

[y]University of Maryland, College Park; e-mail: cropper@rff.org.

[z]Toulouse School of Economics; e-mail: christian.gollier@tse-fr.edu.

[§]London School of Economics; e-mail: b.groom@lse.ac.uk.

[ffi]Columbia Business School; e-mail: gmh1@columbia.edu.

[k]Nicholas School of the Environment, Duke University; e-mail: richard.newell@duke.edu.

#Cowles Foundation, Yale University; e-mail: william.nordhaus@yale.edu.

**Sloan School of Management, Massachusetts Institute of Technology; e-mail: rpindyck@mit.edu.

[yy]Sanford School of Public Policy, Duke University; e-mail: billy.pizer@duke.edu.

[zz]University of Arizona, Tucson; e-mail: pportney@email.arizona.edu.

[§§]University of Gothenburg; e-mail: thomas.sterner@economics.gu.se.

[fiffi]University of Sussex; e-mail: richard.tol@esri.ie.

[kk]Harvard University; e-mail: weitzman@fas.harvard.edu.

At a workshop held at Resources for the Future in September 2011, twelve of the authors were asked by the US Environmental Protection Agency (EPA) to provide advice on the principles to be used in discounting the benefits and costs of projects that affect future generations. Maureen L. Cropper chaired the workshop. Much of the discussion in this article is based on the authors' recommendations and advice presented at the workshop.

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SOCIAL COST OF CARBON

THE GLOBAL COST OF CLIMATE CHANGE AND LOCAL IMPACTS ON COMMUNITIES

EPIC

ENERGY POLICY INSTITUTE
AT THE UNIVERSITY OF CHICAGO

THE UNIVERSITY OF CHICAGO

nature climate change

LETTERS

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Temperature impacts on economic growth warrant stringent mitigation policy

Frances C. Moore[1,2]* and Delavane B. Diaz[3]

Integrated assessment models compare the costs of greenhouse gas mitigation with damages from climate change to evaluate the social welfare implications of climate policy proposals and inform optimal emissions reduction trajectories. However, these models have been criticized for lacking a strong empirical basis for their damage functions, which do little to alter assumptions of sustained gross domestic product (GDP) growth, even under extreme temperature scenarios[1–3]. We implement empirical estimates of temperature effects on GDP growth rates in the DICE model through two pathways, total factor productivity growth and capital depreciation[4,5]. This damage specification, even under optimistic adaptation assumptions, substantially slows GDP growth in poor regions but has more modest effects in rich countries. Optimal climate policy in this model stabilizes global temperature change below 2 °C by eliminating emissions in the near future and implies a social cost of carbon several times larger than previous estimates[6]. A sensitivity analysis shows that the magnitude of climate change impacts on economic growth, the rate of adaptation, and the dynamic interaction between damages and GDP are three critical uncertainties requiring further research. In particular, optimal mitigation rates are much lower if countries become less sensitive to climate change impacts as they develop, making this a major source of uncertainty and an important subject for future research.

Integrated assessment models (IAMs) have traditionally captured the negative impacts of climate change with a damage function that relates global temperature change to a loss of current economic output. This formulation captures the transient effects of climate on the economy such as lost agricultural output, increased cooling demand, or lower worker productivity due to hotter temperatures[7–9]. Factors of production, namely labour and capital, and their total factor productivity (TFP) are not directly impacted, meaning that climate change has no effect, or only a very weak effect, on GDP growth. Two IAMs recently used for the US government social cost of carbon (SCC) estimate, FUND and PAGE, assume that GDP growth is entirely exogenous[10,11]. In the DICE model, labour and TFP are specified exogenously and capital formation is determined through endogenous investment decisions[5]; temperature shocks can therefore alter economic growth through capital stock reductions, but this effect is small and indirect[12].

Damages from climate change that directly affect growth rates have the potential to markedly increase the SCC because each temperature shock has a persistent effect that permanently lowers GDP below what it would otherwise be (Supplementary Fig. 1). Continued warming therefore has a compounding effect over time, so that even very small growth effects result in much larger impacts than the traditional damage formulation[12]. Examples of pathways by which temperature could affect the growth rate of GDP include damage to capital stocks from extreme events, reductions in TFP because of a change in the environment that investments were originally designed for, or slower growth in TFP because of the diversion of resources away from research and development and towards climate threats[1]. Empirical evidence that these impacts exist is mounting. Two studies have found a reduced-form relationship between temperature shocks and GDP growth[4,13], and other studies have demonstrated plausible pathways including increasing conflict risk[14] and changes in labour supply[15]. Previous work has demonstrated that DICE results are sensitive to the inclusion of growth impacts[12,16], but no previous studies have calibrated these damages using empirically grounded results from the econometrics literature. Given the potentially first-order impacts of these growth effects, understanding their implications for climate policy is of critical importance.

Table 1 | Parameters used to calibrate the gro-DICE damage functions, reported in Dell *et al.* Table 3, column 4 (ref. 4).

	Effect 1 °C temp increase on GDP growth rates ($_0$)	Effect 1 °C temp increase on economic output ($_0$)
Poor	1.171 pp	0.426%
Rich	0.152 pp	0.371%

This specification includes 10 temperature lags and no precipitation controls. A brief summary of the estimation strategy used in ref. 4 is given in the Supplementary Information. pp: percentage point.

Here we examine alternative formulations of the DICE damage function based on empirical estimates of the impact of inter-annual temperature variability on national economic output and growth rates by Dell and colleagues[4]. They find large, statistically significant negative effects of hot temperatures on growth rates in poor countries, smaller effects in rich countries, and mixed effects on output (Table 1). To implement these parameters in an IAM, we develop a two-region version of DICE (ref. 17; DICE-2R). We then modify the damage pathway so that warming affects either TFP growth or capital depreciation as per results in ref. 4 (gro-DICE) and investigate sensitivities to the parameters used by Dell et al.[4] (Methods). We present results of the TFP pathway here, but the capital pathway gives quantitatively similar results and is discussed further in the Methods and Supplementary Information.

As Dell et al.[4] use transient and largely unanticipated weather shocks in their estimation, the growth-rate sensitivities (reduction

[1]Emmett Interdisciplinary Program in Environment and Resources, Stanford University, California 94305, USA. [2]Center on Food Security and Environment, Stanford University, California 94305, USA. [3]Department of Management Science and Engineering, Stanford University, California 94305, USA.
*e-mail: fcmoore@stanford.edu

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THE USE AND MISUSE OF MODELS FOR CLIMATE POLICY

Robert S. Pindyck

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A RAPID ASSESSMENT MODEL FOR UNDERSTANDING THE SOCIAL COST OF CARBON*

STEPHEN C. NEWBOLD[†], CHARLES GRIFFITHS, CHRIS MOORE,
ANN WOLVERTON and ELIZABETH KOPITS

U.S. EPA, National Center for Environmental Economics
EPA West Building — 4316T, 1301 Constitution Avenue NW
Washington, DC 20460, USA
[†]newbold.steve@epa.gov

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The "social cost of carbon" (SCC) is the present value of the stream of future damages from one additional unit of carbon emissions in a particular year. This paper develops a rapid assessment model for the SCC. The model includes the essential ingredients for calculating the SCC at the global scale and is designed to be transparent and easy to use and modify. Our goal is to provide a tool to help analysts and decision-makers quickly explore the implications of various modeling assumptions for the SCC. We use the model to conduct sensitivity analyses over some of the key input parameters, and we compare estimates of the SCC under certainty and uncertainty in a Monte Carlo analysis. We find that, due to the combined effects of uncertainty and risk aversion, the certainty-equivalent SCC can be substantially larger than the expected value of the SCC. In our Monte Carlo simulation, the certainty-equivalent SCC is more than four times larger than the expected value of the SCC, and we show that this result depends crucially on how the uncertain preference parameters are handled. We also compare the approximate present value of benefits estimated using the SCC to the exact value of compensating variation in the initial period for a wide range of hypothetical emission reduction policies.

Keywords: Climate change; integrated assessment model; social cost of carbon; climate sensitivity.

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CALCULATING THE SOCIAL COSTS OF CARBON WITHOUT KNOWING PREFERENCES COMMENT ON "A RAPID ASSESSMENT MODEL FOR UNDERSTANDING THE SOCIAL COST OF CARBON"

REYER GERLAGH
Tilburg Sustainability Center, CentER, Economics Department
Tilburg University, Tilburg, Netherlands
R.Gerlagh@uvt.nl

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The Social Costs of Carbon (SCC) equals the marginal welfare loss associated with one unit of emitted CO_2, divided by the marginal welfare gain associated with one unit of consumption. In stochastic assessments, both the nominator and denominator can depend on uncertain parameters; specifically they depend on the (implicit) scaling of the welfare function with the parameters. I discuss some pitfalls when calculating the expected value or the certainty equivalent of the SCC, and show that a mistaken procedure easily leads to very high or very low estimates for the SCC. I use the paper by Newbold et al. (2013) as an illustration.

Keywords: Climate change; social cost of carbon; integrated assessment models; uncertainty.

1. Introduction

It is common to calculate the expected value for the social costs of carbon (SCC), but the precise meaning is not so clear.[1] Here, I will discuss the assumptions needed to calculate an expected SCC measure, and I will show that violation of these assumptions results in misleading estimates for the SCC. The SCC plays an increasingly important role in climate policy recommendations, and it is essential that we understand its fundamentals and identify potential mistakes. As a case in point, I will show that the measure developed by Newbold et al. (2013) for the "Certainty-Equivalent" SCC, which returns a very high level for the SCC compared to previous estimates, is based on a mistaken procedure and does not provide a proper estimate for the SCC.

Metrics matter when taking expectation. Assume, we have equal probability that climate sensitivity is 1 K (Kelvin) or 5 K, so that the expected climate sensitivity is 3 K.

[1]See van den Bijgaart et al. (2013) for a simple framework and a quick assessment of the major uncertainties and their role in the distribution function and expected value of the SCC.

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What Do We Learn from the Weather? The New Climate–Economy Literature

Melissa Dell, Benjamin F. Jones, and Benjamin A. Olken*

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Is There an Energy Efficiency Gap?

Hunt Allcott and Michael Greenstone

Many analysts of the energy industry have long believed that energy efficiency offers an enormous "win-win" opportunity: through aggressive energy conservation policies, we can both save money and reduce negative externalities associated with energy use. In 1979, Pulitzer Prize-winning author Daniel Yergin and the Harvard Business School Energy Project made an early version of this argument in the book *Energy Future*:

> If the United States were to make a serious commitment to conservation, it might well consume 30 to 40 percent less energy than it now does, and still enjoy the same or an even higher standard of living . . . Although some of the barriers are economic, they are in most cases institutional, political, and social. Overcoming them requires a government policy that champions conservation, that gives it a chance equal in the marketplace to that enjoyed by conventional sources of energy.

Thirty years later, consultancy McKinsey & Co. made a similar argument in its 2009 report, *Unlocking Energy Efficiency in the U.S. Economy*:

> Energy efficiency offers a vast, low-cost energy resource for the U.S. economy—but only if the nation can craft a comprehensive and innovative approach to

■ *Hunt Allcott is Assistant Professor of Economics, New York University, New York City, New York. Michael Greenstone is 3M Professor of Environmental Economics, Massachusetts Institute of Technology, Cambridge, Massachusetts. Allcott is a Faculty Research Fellow and Greenstone is a Research Associate, both at the National Bureau of Economic Research, Cambridge, Massachusetts. Their e-mail addresses are ⟨hunt.allcott@nyu.edu⟩ and ⟨mgreenst@mit.edu⟩.*
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Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program

Meredith Fowlie, Michael Greenstone, and Catherine Wolfram*

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Abstract

Conventional wisdom suggests that energy efficiency (EE) policies are beneficial because they induce investments that pay for themselves and lead to emissions reductions. However, this belief is primarily based on projections from engineering models. This paper reports on the results of an experimental evaluation of the nation's largest residential EE program conducted on a sample of more than 30,000 households. The findings suggest that the upfront investment costs are about twice the actual energy savings. Further, the model-projected savings are roughly 2.5 times the actual savings. While this might be attributed to the "rebound" effect – when demand for energy end uses increases as a result of greater efficiency – the paper fails to find evidence of significantly higher indoor temperatures at weatherized homes. Even when accounting for the broader societal benefits of energy efficiency investments, the costs still substantially outweigh the benefits; the average rate of return is approximately -9.5% annually.

* We received many helpful comments from seminar participants at Carnegie Mellon, Columbia University, ETH Zurich, National University of Singapore, NBER Summer Institute, Resources for the Future, the University of Basel, the University of Maryland, the University of Michigan, and the University of Wisconsin. The authors gratefully acknowledge the financial support of the Alfred P. Sloan Foundation, the MacArthur Foundation, the Rockefeller Foundation and the UC Berkeley Energy and Climate Institute, and institutional support from the Poverty Action Lab (JPAL) at MIT, the Center for Local, State, and Urban Policy (CLOSUP) at the University of Michigan, and the Energy Institute at Haas. We thank James Gillan, Brian Goggin, Walter Graf, Erica Myers, Daniel Stuart, and Matthew Woerman for excellent research assistance. We are indebted to Jesse Worker for outstanding management of a challenging project. Finally, we thank our contacts at both our partner utility and the community action agencies, without whom this project would not have been possible.

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Discounting disentangled: an expert survey on the determinants of the long-term social discount rate

Moritz Drupp, Mark Freeman,
Ben Groom and Frikk Nesje

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DEVELOPING INNOVATIVE ANSWERS TO TODAY'S COMPLEX ENVIRONMENTAL CHALLENGES

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Discussion Paper 15-62

The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

Gilbert Metcalf
Tufts University

James Stock
Harvard University

HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

heep@harvard.edu
http://heep.hks.harvard.edu

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John Weyant*

Integrated assessment of climate change: state of the literature

Abstract: This paper reviews applications of benefit-cost analysis (BCA) in climate policy assessment at the US national and global scales. Two different but related major application types are addressed. First there are global-scale analyses that focus on calculating optimal global carbon emissions trajectories and carbon prices that maximize global welfare. The second application is the use of the same tools to compute the social cost of carbon (SCC) for use in US regulatory processes. The SCC is defined as the climate damages attributable to an increase of one metric ton of carbon dioxide emissions above a baseline emissions trajectory that assumes no new climate policies. The paper describes the three main quantitative models that have been used in the optimal carbon policy and SCC calculations and then summarizes the range of results that have been produced using them. The results span an extremely broad range (up to an order of magnitude) across modeling platforms as well as across the plausible ranges of input assumptions to a single model. This broad range of results sets the stage for a discussion of the five key challenges that face BCA practitioners participating in the national and global climate change policy analysis arenas: (1) including the possibility of catastrophic outcomes; (2) factoring in equity and income distribution considerations; (3) addressing intertemporal discounting and intergenerational equity; (4) projecting baseline demographics, technological change, and policies inside and outside the energy sector; and (5) characterizing the full set of uncertainties to be dealt with and designing a decision-making process that updates and adapts new scientific and economic information into that process in a timely and productive manner. The paper closes by describing how the BCA models have been useful in climate policy discussions to date despite the uncertainties that pervade the results that have been produced.

Keywords: benefit-cost analysis; climate change; integrated assessment; optimal carbon emissions; social cost of carbon.

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***Corresponding author: John Weyant,** Department of Management Science and Engineering, Room 260, Huang Engineering Center, Stanford University, Stanford, CA 94305-4026, USA, Phone: +1 650 723 0645, Fax: +1 650 723 3506, e-mail: weyant@stanford.edu

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Is There an Energy Efficiency Gap?

Hunt Allcott and Michael Greenstone

Many analysts of the energy industry have long believed that energy efficiency offers an enormous "win-win" opportunity: through aggressive energy conservation policies, we can both save money and reduce negative externalities associated with energy use. In 1979, Pulitzer Prize-winning author Daniel Yergin and the Harvard Business School Energy Project made an early version of this argument in the book *Energy Future*:

> If the United States were to make a serious commitment to conservation, it might well consume 30 to 40 percent less energy than it now does, and still enjoy the same or an even higher standard of living . . . Although some of the barriers are economic, they are in most cases institutional, political, and social. Overcoming them requires a government policy that champions conservation, that gives it a chance equal in the marketplace to that enjoyed by conventional sources of energy.

Thirty years later, consultancy McKinsey & Co. made a similar argument in its 2009 report, *Unlocking Energy Efficiency in the U.S. Economy*:

> Energy efficiency offers a vast, low-cost energy resource for the U.S. economy—but only if the nation can craft a comprehensive and innovative approach to

■ *Hunt Allcott is Assistant Professor of Economics, New York University, New York City, New York. Michael Greenstone is 3M Professor of Environmental Economics, Massachusetts Institute of Technology, Cambridge, Massachusetts. Allcott is a Faculty Research Fellow and Greenstone is a Research Associate, both at the National Bureau of Economic Research, Cambridge, Massachusetts. Their e-mail addresses are ⟨hunt.allcott@nyu.edu⟩ and ⟨mgreenst@mit.edu⟩.*

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Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program

Meredith Fowlie, Michael Greenstone, and Catherine Wolfram*

June 2015

Abstract

Conventional wisdom suggests that energy efficiency (EE) policies are beneficial because they induce investments that pay for themselves and lead to emissions reductions. However, this belief is primarily based on projections from engineering models. This paper reports on the results of an experimental evaluation of the nation's largest residential EE program conducted on a sample of more than 30,000 households. The findings suggest that the upfront investment costs are about twice the actual energy savings. Further, the model-projected savings are roughly 2.5 times the actual savings. While this might be attributed to the "rebound" effect – when demand for energy end uses increases as a result of greater efficiency – the paper fails to find evidence of significantly higher indoor temperatures at weatherized homes. Even when accounting for the broader societal benefits of energy efficiency investments, the costs still substantially outweigh the benefits; the average rate of return is approximately -9.5% annually.

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